Quartz Veining in Multiply-folded Greywackes, Bermagui, New South Wales, Australia

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Quartz veins subparallel and subnormal to fold axes dominate veining at Bermagui. The widespread development of stripy cleavage (S_1) has enabled the timing between this cleavage and quartz veining to be better constrained than any other relationship. Most quartz veins have formed syn-S_1, but some developed throughout the deformation history.

Oxygen isotope studies and preliminary fluid inclusion studies indicate temperatures around 300°C, consistent with the greenschist facies mineralogy. The high and uniform $\delta^{18}0$ values indicate deposition of quartz over a narrow temperature interval from a fluid reservoir in the greywacke pile. These quartz-bearing fluids were mobilized during widely-separated orogenies in the Siluro-Devonian and early Carboniferous

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INTRODUCTION

Different interpretations have been made of the deformation history of the undifferentiated Ordovician greywackes and slate at Bermagui. Williams (1972) proposed a two phase deformation history and Powell (1983) proposed a five-phase model. Discussion of quartz veining within the context of these models was limited. Williams (1972) recognized the importance of quartz migration to the development of different foliation morphologies, but did not consider quartz veining within this model. Powell and Rickard (1985) identified some quartz veins as post-S_0, pre-S* and pre-S_1, as the quartz veins were isoclinally microfolded, with S* axial planar, and these veins were dissolved along S_1 surfaces. Studies of deformed coastal Ordovician sequences in north-east Victoria indicated that quartz veins formed pre- and post-S* (Wilson and Hedouville, 1985, figs 3d, 8).

This study clarifies the relationship between quartz veining and the folds and foliations in two coastal exposures at Bermagui. One of these exposures contains F_1 folds, while the other exposure exhibits F_1 to F_4 folds, enabling partial understanding of the geometrical and temporal relationship between quartz veining and folding-foliation development. The irregular development of quartz veins, and the rarity of suitable cross-cutting quartz veins, prevents complete resolution of the temporal relationships.

Regional and Local Geology

The mesoscopic folds containing quartz veins crop out at Bermagui in Ordovician greywacke and slate on the eastern margin of the Lachlan Fold Belt. This greywacke sequence has been subjected to greenschist facies metamorphism (Williams, 1971).

Williams (1971) recognized two generations of folds, with the meridional regional folds having an antiformal crest just offshore from Bermagui headland (Fig. 1) and a synformal crest about one and a half kilometres inland. This regional fold pattern was interpreted to be a second-generation structure. These later folds either refolded earlier folds to a recumbent attitude or reduced the interlimb angle of the earlier folds. Recumbent F_1 folds generally occur on the limbs of F_2 folds and isoclinal F_1 folds generally occur in the hinge of F_2 folds (Williams, 1971). Powell (1983) recognized five phases of deformation at Bermagui. The first phase resulted in the development of a foliation without exposed folds (Powell and Rickard, 1985) whilst the second to fourth phases resulted in folds with foliations and the last phase resulted in kinking.

This study concentrated on two localities, the headland just east of the breakwater at Bermagui and the wave-cut platform and cliff on the north side of Zane Grey Pool about two kilometres south of Bermagui (Fig. 1; Powell, 1983). Remapping of foreshore exposures confirms the overall geology as reported by Powell (1983, figs 52, 53). The greywackes on the headland adjacent to the breakwater exhibit one generation of asymmetric, east-verging, upright mesoscopic folds (half wavelength ~ 5-7m) with axial surface differentiated crenulation cleavage (stripy cleavage, Figs 4**a**, **b**). The sandstone beds hosting quartz veins are usually less than half a metre thick and rarely up to one metre thick. The sequence north of Zane Grey Pool exhibits three generations of mesoscopic folds (F_1, F_2, F_3) varying from upright to recumbent (half wavelength ~ 5-7 m), with axial surface differentiated crenulation cleavage (stripy cleavage, S_1) or mm- to cm-spaced crenulation cleavage (S_2, S_3).

The F_1 folds at Zane Grey Pool have been refolded co-axially to form gently-plunging, upright to overturned asymmetric folds with overprinting axial surface spaced crenulation cleavage (Fig. 3**a**). The wave-cut platform exhibits both fold- and fault-related quartz veining. There are far fewer quartz veins and less variety of orientations of quartz veins at Zane Grey Pool exposures compared with the Bermagui headland exposures.

Poles to bedding for the Bermagui headland indicate that the upright F_1 folds plunge gently to the north-northeast (Fig. 2**a**). The contoured stereographic projection of poles to bedding for Zane Grey Pool indicates that F_2 plunge gently southsouthwest, and are thus coaxial with F_1 folds (Fig. 2**b**). The plots of foliations demonstrate that the stripy cleavage identified on Bermagui headland (Fig. 2**c**), which is axial planar to F_1 folds, has been folded about F_2 folds, and the S_2 and S_3 spaced crenulation cleavages are oriented either northwest-southeast or northeast-southwest (Fig. 2**d**). These stereographic projections support the field observations that F_1 folds were coaxially refolded by F_2 folds and neither of these two earlier fold phases is significantly affected by F_3 or F_4 folds or later kinking.

Methods and Methodology

Quartz Veining

In folded greywackes at both localities it is possible to define quartz-vein sets consisting of clusters of quartz veins of a similar size and orientation within the 0.5-1.0m thick, arenite beds. In up to 5m-wide sections across the hinge zone or limbs of these folds, representative quartz veins from a set were measured, and their cross-cutting relationships to other sets were established wherever possible.

Any sets striking 22.5° either side of the hinge line trend are considered subparallel sets (P sets), any sets 22.5° either side of normal to the hinge line trend are considered subnormal sets (N sets) and any sets intermediate between these are considered oblique sets (0 sets). Temporal relationships were established on the basis of four main types of intersections: 1) one set truncates another, 2) one set cuts the other with visible displacement, 3) one set cuts another without visible displacement, but fibres in one set are continuous across that vein at the intersection or 4) one set cuts another without visible displacement, fibres or any other diagnostic criterion. The overall sequence of sets from a number of exposures of the same limb or hinge zone was determined using a three by three matrix. This relates the number of sets doing the cutting on the abscissa to the

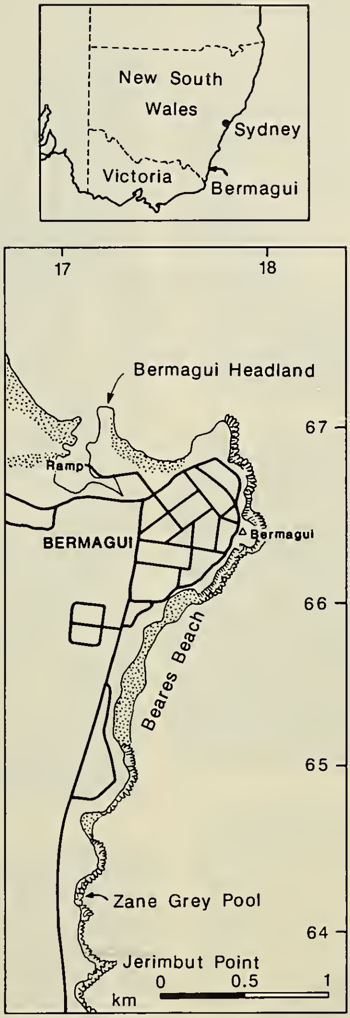

Fig. 1. Locality map showing the position of Bermagui on the New South Wales south coast and the named headlands at Bermagui.

number of sets being cut on the ordinate. This method provides an unambiguous guide to the order of formation of different sets.

There are planar and *en echelon* N, P and O quartz veins at Bermagui. There is also contemporaneous development of quartz veins at an angle less than 45° to the planar O, P and N sets. These are called conjugate sets to indicate their relationship to the nominated set.

The Zane Grey Pool quartz veins are dominantly planar N and P sets (Fig. 3) and rarely *en echelon* N and P sets. On Bermagui headland there are planar O, N and P sets occasional *en echelon* N and O sets (Figs 4 and 5) and rare quartz veins conjugate to the planar O, N and P sets (Figs 5**a**, **d**, Table 1).

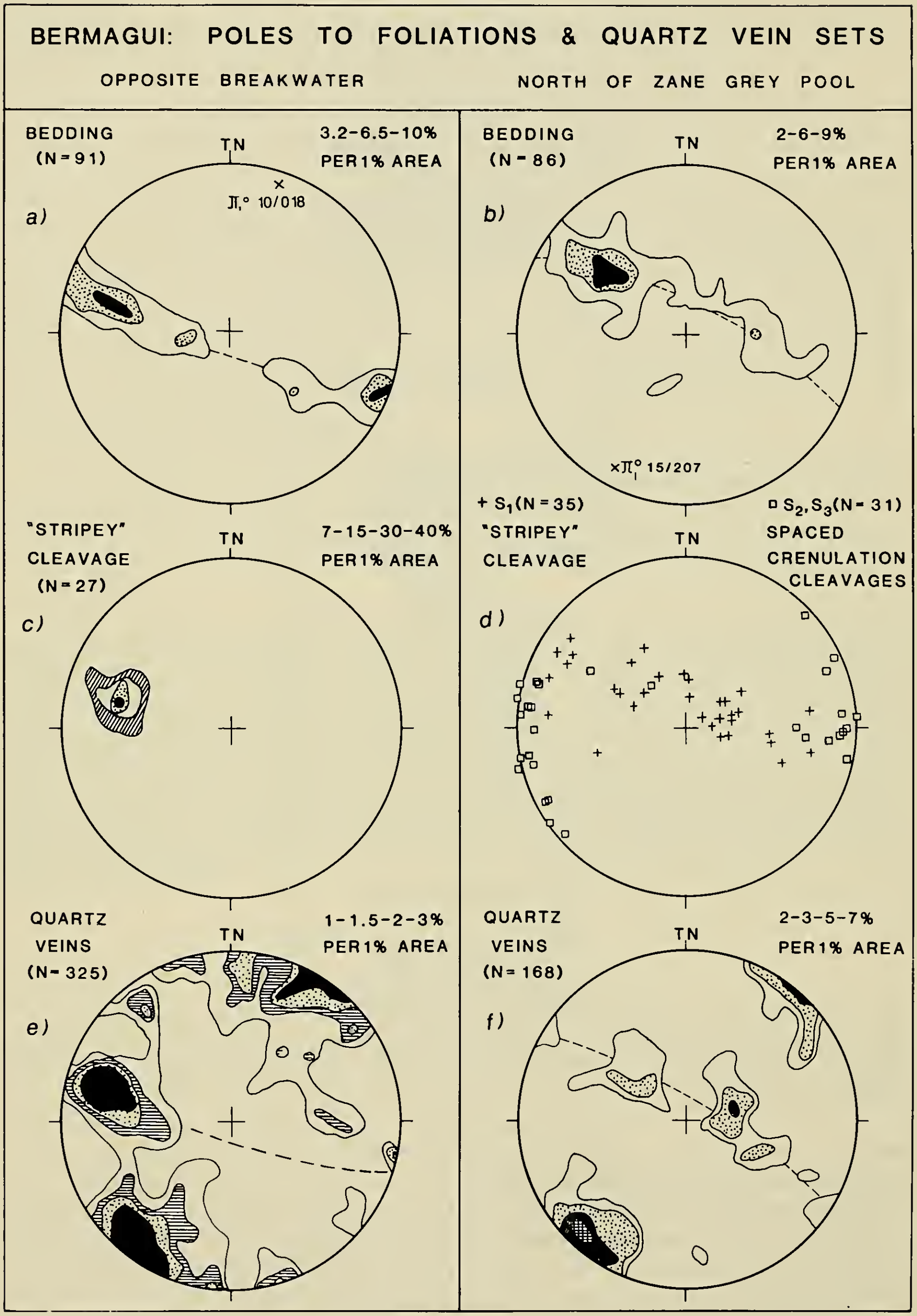

Fig. 2. Contoured stereographic projection (lower hemisphere) of poles to bedding (a, b), cleavages (c, d) and quartz veins (e, f) for Bermagui headland opposite the breakwater and north of Zane Grey Pool. N = number of readings.

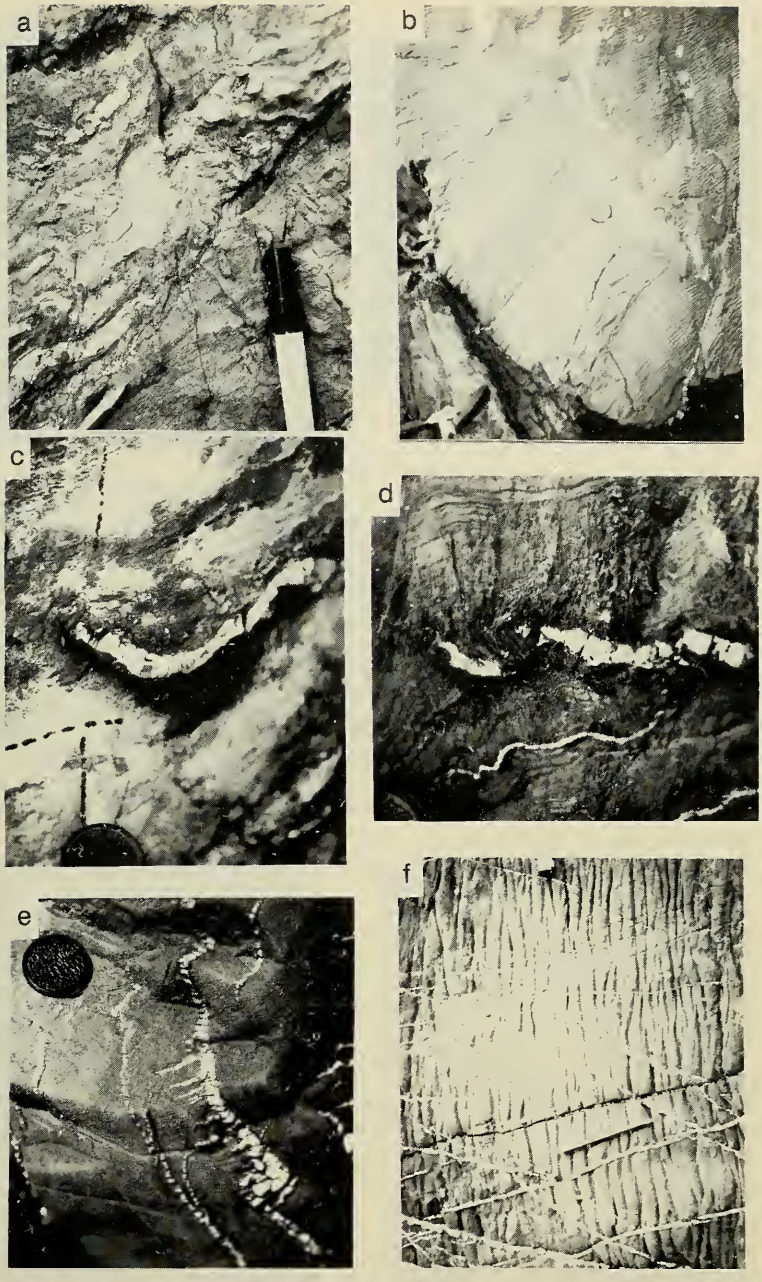

Fig. 3. Quartz veins and foliations at Zane Grey Pool. **(a)** Bedding trends top right to lower left and spaced crenulation cleavage trends top to bottom. The S* cleavage trends left to right and intersects the bedding at a low angle and is partly defined by quartz veins. Black marking pen cap is 45mm long. **(b)** Limb to hinge zone of inclined F_1 fold with fanned stripy cleavage and extensional P quartz veins. Lens cap is 50mm across. **(c)** Folded quartz vein with spaced crenulation cleavage axial surface to open fold (solid line). The dashed line is parallel to bedding. Lens cap is 50mm across. **(d)** *En echelon* P quartz veins disrupt S*, S_3 and S_4 foliations. The quartz vein at left of centre is 50mm long. **(e)** P quartz veins with pinnate branches on the limb of an F_1 fold. Lens cap is 50mm across. **(f)** Prominent stripy cleavage from top to bottom is dissected by conjugate N quartz veins. Scale has 10mm divisions.

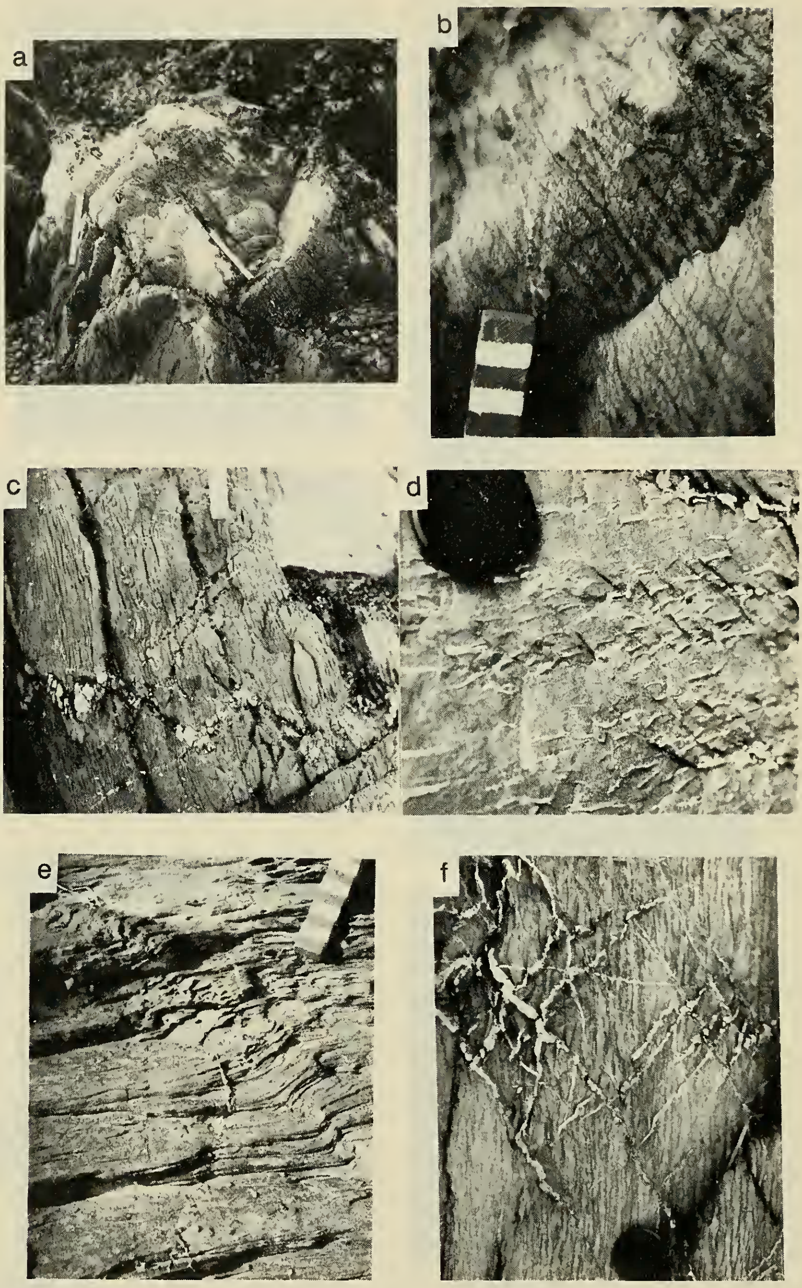

Fig. 4. Folds, kinks, quartz veins and stripy cleavage at Bermagui headland. **(a)** Asymmetric F_1 fold with axial surface stripy cleavage (see **b**). Scale has 10mm divisions. **(b)** Close up view of stripy cleavage (upper left to lower right) and bedding (lower left to upper right) on the limb of an F_1 fold. Scale has 10mm divisions. **(c)** Stripy cleavage (top to bottom) dissected by folded N quartz vein. Scale has 10mm divisions. **(d)** Stripy cleavage dissecting *en echelon* N veins. Lens cap is 50mm across. **(e)** *En echelon* N veins pass through kink without deflection. Scale divisions are 10mm. **(f)** Stripy cleavage from top to bottom. There are two O sets one trending top right to lower left (O_1) and the other trending top left to lower right (O_2). The O_1 set shows microfolding and dissection by the stripy cleavage. Lens cap is 50mm across.

Oxygen Isotope Studies

A study of the oxygen isotope relationship between variously oriented quartz veins in the limbs and hinge zone of F_1 folds at Bermagui headland and in F_1 and F_2 folds at Zane Grey Pool was carried out to determine the temperature and source of the fluid from which the quartz veins originated.

Oxygen isotope analyses of vein quartzes were performed at the University of Queensland using standard techniques (Clayton and Mayeda, 1963) and are reported in per mil relative to SMOW (Table 2). Using the quartz-water fractionation of Matsuhisa *et al.* (1979), fluid isotopic compositions were calculated from the mean values for quartz isotopic data at the model temperature 250-300°C (Tables 2 and 3). The errors in the fluid isotopic compositions reflect: (1) the range of quartz $\delta^{18}0$ values, at one standard deviation, and (2) the model temperature interval. This methodology should give maximum error values for the calculated fluid isotopic compositions because the range of mineral isotopic values reflects the temperature regime as well as the fluid composition during quartz veining.

Fluid Inclusion Studies

Over twenty quartz veins were sampled at Bermagui but only three proved to have fluid inclusions large enough for use on the heating stage. These inclusions appear to be primary and not secondary or pseudosecondary (Eadington and Wilkins, 1980). The two quartz veins from Bermagui headland were *en echelon* N and P veins shown by field examination to be syn- or post-F_1 and pre-F_2 (Fig. 6, C1 and Qϕ). The single vein from Zane Grey Pool is an *en echelon* N vein in a F_1 syncline and formed syn- or post-F_1 and pre-F_2 (Fig. 6, LLϕ). These veins are the dominant quartz veins at Bermagui.

Results

Quartz Veining

It is possible to construct a chronological sequence of development of cleavages and quartz veins for the Bermagui headland, and to a lesser extent for the Zane Grey Pool exposures. The widespread development of stripy cleavage (S_1) enables rapid assessment of the timing between quartz vein formation and stripy cleavage development. The dominant N and P sets on Bermagui headland show examples of dissolution of these quartz veins adjacent to the stripy cleavage (Figs 4**d**, **f**) and other instances where dissection has not occurred. Any quartz vein affected by the stripy cleavage must have formed pre- or early syn-S_1, whilst those quartz veins unaffected by the stripy cleavage must have formed post-S_1. In the few areas where kinking developed on Bermagui headland, P and N sets show rotation into the kink planes. There are rare instances where *en echelon* N quartz veins cross-cut a kink band and are affected by the kinking (Fig. 4**e**). Thus P and N quartz veins on Bermagui headland were mostly formed pre- to syn-S_1 and pre-kinking. Kinking occurred as the final event in the deformation history (Powell, 1983). Therefore it is not surprising that most of the quartz veins are formed pre-kinking. The mesoscopic folds on Bermagui headland are F_1 folds with axial planar stripy cleavage (Fig. 4**a**). If most quartz veins are pre- or syn-S_1 then this indicates that most quartz veins were formed pre- or syn-F_1.

From the limited number of quartz veins intersecting in the sequence at Zane Grey Pool, it can be shown that P sets usually cut N sets, although there are instances where N and P veins were formed contemporaneously (Fig. 5**b**) or where N veins cut P veins (Fig. 5**c**). Generally O sets cut P sets, leading to a simple three-stage sequence of sets formation, i.e. N to P to O. Since previous studies of more prolifically-developed quartz veins indicate extensive overlapping in the time of formation of O, P and N veins in

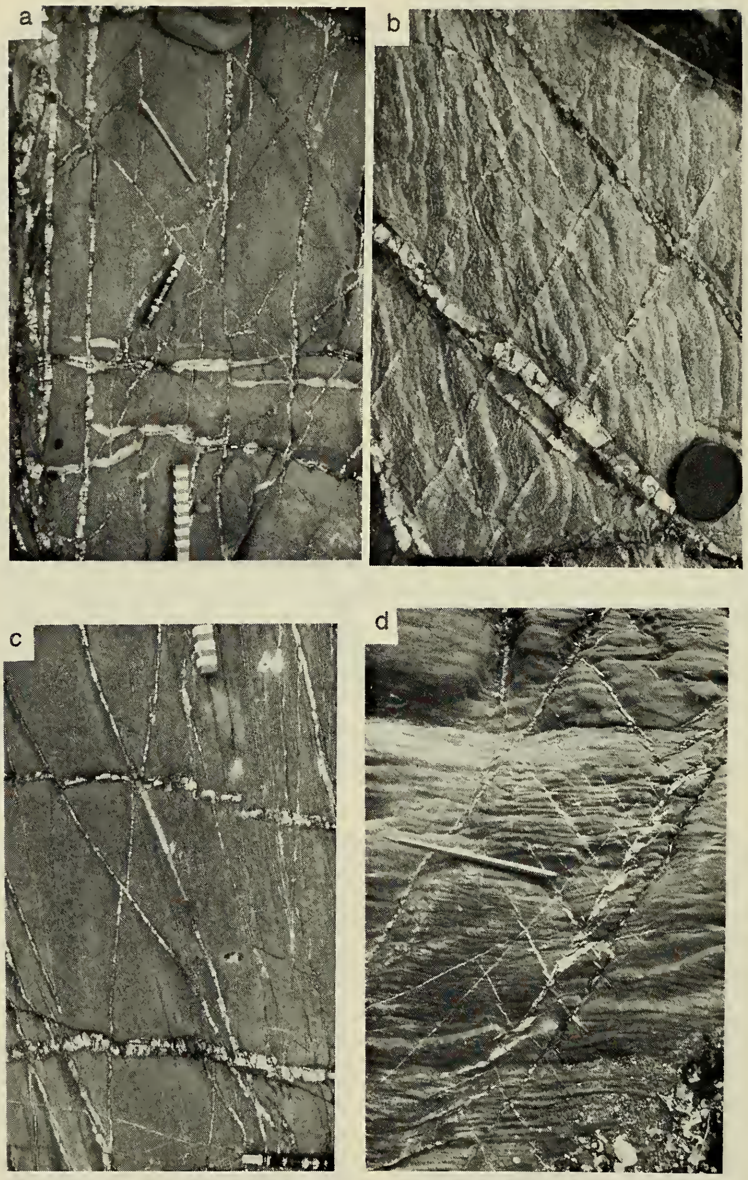

Fig. 5. Morphology and temporal relationships between quartz veins at Bermagui headland. **(a)** P veins (scale) formed syn- to post- the conjugate (pencil and texta) O veins. Note in the centre of the plate displacement of conjugate O veins (pencil). Scale has 10mm divisions. **(b)** Stripy cleavage — bedding intersection lineation trends top to bottom and is dissected by thicker N veins (middle left to bottom right) and thinner P veins (top right to lower left). Some N veins are cut by P veins and cut other P veins. Lens cap is 50mm across. **(c)** Scale parallel to F_1 fold axis and bisects the acute angle between conjugate O veins and is parallel to thin P veins. Thicker N veins show dissection in some areas (upper centre) and are not disrupted in other areas (bottom). Scale divisions are 10mm. **(d)** Stripy cleavage-bedding intersection lineation trends left to right. *En echelon* O sets trend top left to bottom right and conjugate planar to *en echelon* O sets trend top right to bottom left. Pencil is 150mm long.

simply folded greywacke sequences (Lennox, 1985; Lennox and Golding, 1989), it is extremely unlikely that this observed order of formation of quartz veins would rigorously apply in different parts of this multiply-folded sequence. The restricted development of F_3 and F_4 folds at Zane Grey Pool prevents an assessment of the relationship between quartz veining and these fold- and foliation-forming events. In rare instances open microfolded quartz veins were observed disrupting the S_1 cleavage in pelites. The S_2-spaced crenulation cleavage is axial surface to these microfolds (Fig. 3**c**). This indicates that some O quartz veins developed post-S_1 and pre- or syn-S_2. Other O and P quartz veins disrupt the S_1 to S_3 fabrics indicating formation post-S_3 (Fig. 3**d**). Normally O and P sets at Zane Grey Pool exposures are folded by mesoscopic F_1 folds or are microfolded by parasitic folds on the limbs of the mesoscopic F_1 folds. The stripy cleavage (S_1) dissects some O and N sets and is truncated by other O and N sets (Fig. 3**f**). Two O and N sets in the Zane Grey Pool exposures are pre- to syn- the first phase of folding and associated cleavage whereas P sets are commonly formed pre-F_1 folding. Some planar vein sets developed as extensional veins in the outer hinge zone of mesoscopic F_1 folds during folding (Fig. 3**b**) and other P veins on the limbs of mesoscopic F_1 folds exhibit pinnate branches indicating some reorientation of the stress field during quartz vein formation.

TABLE 1

Quartz vein abundances, Bermagui

Occurrence	Bermagui headland	Zane Grey Pool
rarely developed	P conjugate P *en echelon*	N *en echelon* P *en echelon*
common	N conjugate O *en echeon* O conjugate N *en echelon*	O conjugate O
abundant	P, N	P, N.

The contoured stereographic projections of poles to quartz veins for Bermagui headland shows three point populations indicative of P and N quartz veins (Fig. 2**e**). Coaxial refolding of F_1 folds would result in little apparent reorientation of N veins on a stereographic projection, because of their attitude to the pole of rotation whereas P veins would be rotated on a stereographic projection. Depending upon the mechanism of folding coaxial refolding may simply move populations of poles of P quartz veins around small circles (Ramsay, 1967). The contoured stereographic projection of poles to quartz veins for Zane Grey Pool is consistent with rotation of mainly P and N veins. This results in a scatter of point populations on the great circle girdle defined from the poles to bedding data indicative of differently-rotated P veins, along with a point concentration due to rotated, but geometrically little modified, N veins near the F_2 fold axis (Fig. 2**f**).

Oxygen Isotopes

Assuming a reasonable deposition temperature of 250-300°C (based on preliminary fluid inclusion data which suggest corrected homogenization temperatures around 300°C, and mineralogy), the calculated fluid composition is 7.2 ± 1.3 (250°C) and 9.1 ± 1.3 (300°C) (n = 21) consistent with metamorphic or magmatic fluids (Taylor, 1979).

The oxygen isotope composition of the quartz averages 16.2 ± 0.2 (n = 21) which lies within the range of mean $\delta^{18}O$ for Victorian gold quartzes (15.8 to 20.2, Wilson and Golding, 1988) considered to have been derived from non-igneous ore fluids. The Cape Liptrap greywacke sequence which was folded by one phase of deformation contains quartz veins with comparable average oxygen isotope composition: 18.4 ± 0.4 (Lennox and Golding, 1989).

TABLE 2

Oxygen isotope data for quartz veins from Bermagui

Locality		Quartz Vein Type	Timing	$\delta^{18}O$ quartz per mil
Bermagui Headland		N	N cuts P	15.8
Fault Zone				16.3
		P	P cuts N	16.0
		P	pre-F_1	16.3
	en echelon	P		16.3
F_1 fold		N		16.0
F_1 fold,	*en echelon*	N		16.6
	en echelon	O		16.0
	conjugate	O		15.8
F_1 fold limb		O		16.2
F_1 fold		P	O cuts P	16.0
F_1 fold limb, *en echelon*		N		15.9
F_1 fold hinge zone		N		16.1
		P	N cuts P	16.1
Zane Grey Pool				
		P	pre-F_2	16.2
		P		16.4
		P	pre-F_2	16.6
F_2 fold		O		16.1
F_1 fold		O		16.0
		P	pre-F_1	16.0
F_1 fold hinge zone		N		16.5

These high and uniform $\delta^{18}O$ values imply deposition of all quartz over a narrow temperature interval from a fluid reservoir with constant $\delta^{18}O$ composition. This constancy is compatible with a metamorphic fluid regime, although a magmatic component cannot be discounted. The homogeneous calculated fluid suggest that local fluid-rock interaction with the diverse host lithologies at Bermagui has not significantly modified fluid composition. Conversely, fluid to rock ratios during deformation may have been sufficiently high to effect equilibration between the different rock types and the infiltrating fluid.

Fluid Inclusions

The average freezing point depressions, corrected homogenization temperatures and calculated fluid salinities are given in Table 4. The homogenization temperatures were corrected using the curves of Potter (1977) assuming a pressure of 200 MPa at the time of entrapment. The range of values for uncorrected homogenization temperature and freezing point depression for fluid inclusions from the three quartz veins are shown in Figs 6a, b. The salinities mean that the fluids from which the quartz veins were derived were poorly saline. Clathrates do not appear to be present in the system nor has the system boiled thus making P-T estimates difficult to determine (Eadington and

TABLE 3

Mean oxygen isotope compositions of quartz vein types, with calculated fluid compositions at 250-300°C

Locality/Vein type		Number of readings	$\delta^{18}O$ quartz $\pm 1\delta$ (per mil)	Calculated $\delta^{18}O$ fluid $\pm (1.1 \pm 1\ \delta)$* (per mil) 300°C	250°C
Bermagui Headland					
N		5	16.1 ±0.3	9 ±1.4	7.2 ±1.4
P		5	16.0 ±0.2	9 ±1.3	7.1 ±1.3
O		3	16.0 ±0.2	8.9 ±1.3	7.0 ±1.3
Fault Zone		1	16.3	9.2	7.3
	Total	14	16.1 ±0.2	9 ±1.3	7.1 ±1.3
Zane Grey Pool					
N		1	16.5	9.4	7.5
P		4	16.3 ±0.3	9.2 ±1.4	7.3 ±1.4
O		2	16.1 ±0.1	9 ±1.2	7.0 ±1.2
	Total	7	16.3 ±0.2	9.2 ±1.3	7.3 ±1.3
Grand Total		21	16.2 ±0.2	9.1 ±1.3	7.2 ±1.3

* Fluid $\delta^{18}O$ values were calculated using the quartz-water fractionation determined by Matsuhisa *et al.* (1979). The equation for temperatures between 250 and 500°C is $1000 \ln \alpha = 3.34(10^6T^{-2})-3.31$.

Wilkins, 1980). The corrected temperatures and pressures are consistent with previous estimates of the greenschist facies metamorphism which affected this rock sequence (Williams, 1972). Thus greenschist facies prograde metamorphism, quartz vein development and folding are contemporaneous events at Bermagui. Basic dyke rocks were sampled in an attempt to identify minerals and use univariant reactions marking transitions between various greenschist facies as a guide to P-T conditions (Liou *et al.*, 1985). These basic rocks have undergone metamorphism and now contain actinolite, chlorite, albite, epidote, calcite and white mica (Offler, pers. comm.), consistent with greenschist facies metamorphism. More sampling of quartz veins and a larger number of heating stage measurements would be required to more confidently constrain estimates of pressure and temperature during prograde metamorphism.

TABLE 4

Heating stage measurements and calculated fluid salinities calculated according to Roedder (1962)

Quartz Vein	Number of readings	Freezing point depression Average °C ±1δ	Corrected Homogenization Temp. Average °C ±1δ	Wt.% NaCl
C1	14	-5.7 ±4.9	303.8 ±45.8	+8.8 ±7.9
LLφ	6	-2.1 ±1.8	312.0 ±7.2	+3.5 ±3.0
Qφ	15	-2.3 ±1.7	341.2 ±11.1	+3.8 ±2.8

DISCUSSION

The abundance of P and N quartz veins at Bermagui reflects the dominance of a regional stress field during folding with σ_1 normal and σ_3 parallel to the developing fold axis. At this time N sets formed. The presence of a localized stress field in the outer arcs

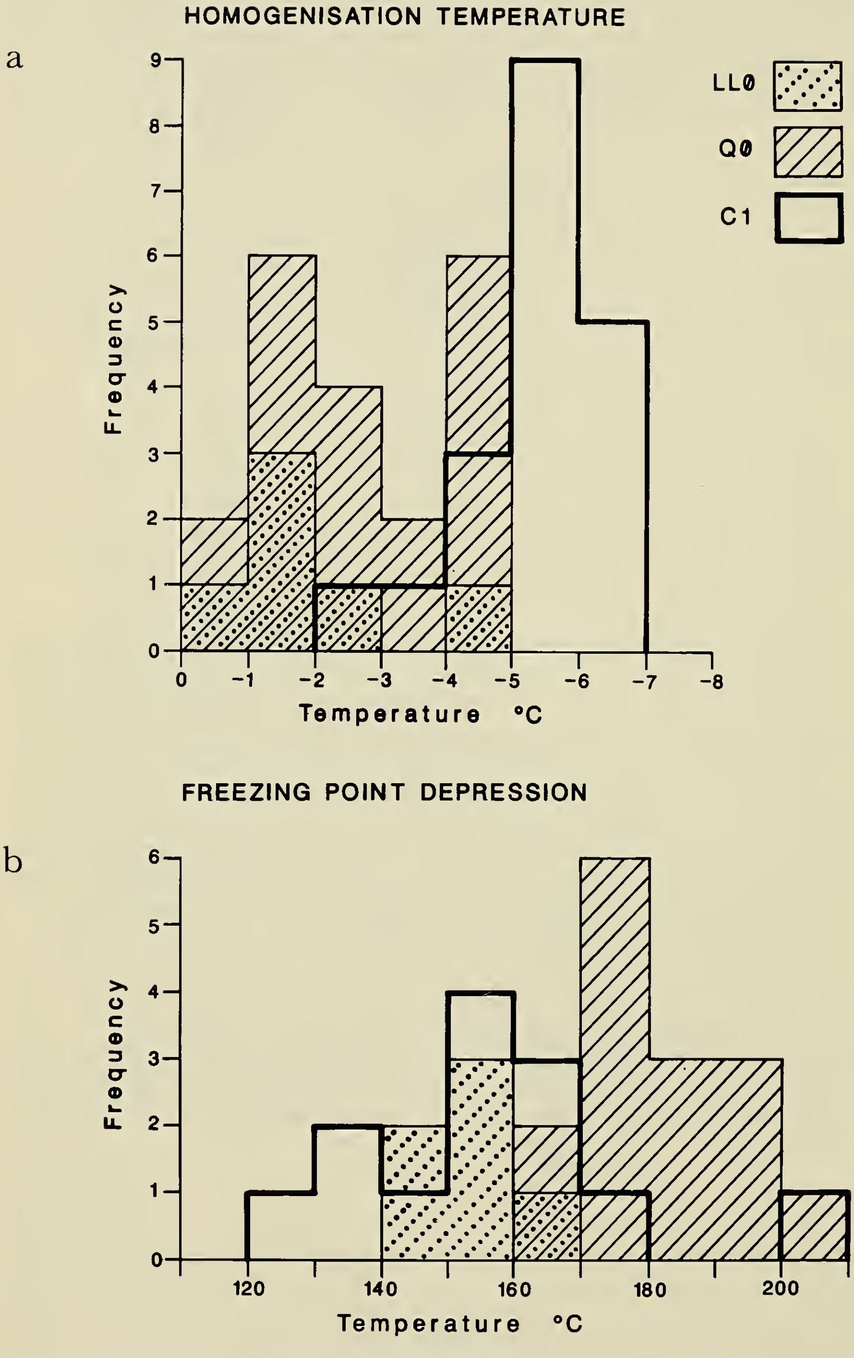

Fig. 6. Histograms (**a**) homogenization temperature for fluid inclusions from the three quartz veins. C1 and Qϕ are from Bermagui headland and LLϕ is from Zane Grey Pool. (**b**) The freezing point depression for the fluid inclusions from the same three quartz veins.

of the developing fold in which S_1 was parallel and S_3 normal to fold axis resulted in time P sets forming. This is comparable with the model proposed on the basis of a much more thorough study of quartz-veined folded greywackes at Cape Liptrap, Victoria (Lennox, 1986; Lennox and Golding, 1989).

The differences between the quartz vein formation in the refolded sequence at Bermagui headland and the multiply-folded sequence at Zane Grey Pool probably reflect the effects of the longer deformation history in the latter locality. The coaxial F_2 refolding at Zane Grey Pool permitted new N, P and O sets to form, whilst the areally restricted F_3 and F_4 folding phases provided more sites for quartz veins.

The presence at Bermagui of more quartz vein morphologies compared with the quartz veins at Cape Liptrap probably also reflects the more complicated multiple folding- and foliation-forming deformation history at Bermagui.

The high and uniform $\delta^{18}0$ values imply deposition of all quartzes over a narrow temperature interval from a fluid reservoir in the greywacke pile. Powell (1983) proposed that F_1 folds formed during the Bowning Orogeny (latest Silurian to earliest Devonian) whilst F_2 folds formed during the Kanimblan Orogeny (early Carboniferous). The oxygen isotope results indicate that fluids mobilized during these widely separated orogenies were similar.

The preliminary fluid inclusion results indicate that the pressure and temperature were around 200-300 MPa and around 300°C during quartz vein formation, consistent with the greenschist facies mineralogy of the greywacke sequence.

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